

## Gas Properties in the Starburst Centers of Barred Galaxies

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**Abstract.** The physical properties of molecular gas can be deduced from the analysis of line intensity ratios, most commonly of the CO isotopomers  $^{12}\text{CO}$  and  $^{13}\text{CO}$ . Barred galaxies, especially those with central starbursts, provide an excellent laboratory to study the changing properties of the gas as it approaches the center. Four galaxies (UGC 2855, UGC 2866, NGC 7479 and NGC 4123) are presented as examples of the results that can be obtained. Special attention is given to the case of (abnormally) high  $^{12}\text{CO}/^{13}\text{CO}$  ( $\mathcal{R}_{12/13}$ ) line ratios (exceeding 20), which may indicate unusual gas properties. Qualitative scenarios for the structure of the ISM explaining a range of values of  $\mathcal{R}_{12/13}$  are discussed.

### 1. Gas flows in bars and changing gas properties

The importance of gas flows in bars as a transfer mechanism of material toward the centers of galaxies, thus fuelling central activity (certainly starburst and possibly AGN-related) and driving galaxy evolution is a well-established fact (e.g. Combes, Dupraz, & Gerin 1990 and references therein, Sakamoto et al. 1999). Gas flowing along the bar loses angular momentum, resulting in a net infall that can be as large as several solar masses per year. Stable, non-intersecting orbits for gas are required; between corotation and the inner Lindblad resonance(s) (ILRs) the gas moves on elongated, bar-sustaining  $x_1$ -orbits. Material may accumulate close to the ILR(s), a ‘spray’ of gas may impact gas still on  $x_1$ -orbits, and characteristic, curved bar shocks, often accompanied by dust lanes, may develop.

Thus, it is easy to see how a *diffuse, unbound* gas component may form along the bar, by either tidal disruption of bound clouds or cloud collisions (Das & Jog 1995, Hüttemeister et al. 2000). In time, as the bar evolves, the bulk of the gas is funneled from the outer  $x_1$ -orbits to an inner family of (slightly anti-bar)  $x_2$ -orbits (e.g. Friedli & Benz 1993). Strength, shape and existence of the bar shock depend on the central mass concentration (see e.g. simulations by Athanassoula 1992).

When the gas approaches the central region, part of it may remain diffuse and unbound. However, it may also pile up and become dense enough to cause

Table 1. Summary of the line ratios observed in the four sample galaxies

Galaxy	$\mathcal{R}_{12/13}(1-0)$	$\mathcal{R}_{12/13}(2-1)$	$^{12}\text{CO}/\text{HCN}(1-0)$
UGC 2855 (center)	$\sim 10$	$\sim 14$	–
UGC 2866 (center)	$\sim 25$	$\sim 10$	$> 38$
NGC 7479 (global)	$\sim 30$	–	–
(center)	$23 (10 - 30)^a$	13	$\sim 25$
(along bar)	$4 - > 40$	–	–
NGC 4123 (center)	26	14	$> 32$
(bar end)	4	4	–

a): For NGC 7479, 10 – 30 is the range encountered in high resolution interferometric observations, while 23 is the average ratio over the central 1 kpc radius.

(and then continue to feed) a nuclear starburst. Clearly, the gas properties within the bar and within the central starburst region should differ. The gas *within* the starburst center is also expected to consist of a number of different phases, e.g. partly diffuse material flowing in from the bar, dense clouds that may represent both hot, actively star forming cores and a dense component that does not (at the moment) form stars and thus cools efficiently, gas exposed to strong shocks and – as the starburst evolves – a component that is strongly affected by the energy released by the young massive stars and thus disrupted. The balance of these phases will change with the state of the burst; therefore the gas properties, if they can be derived accurately enough, can be used as an indicator of starburst evolution.

*Line intensity ratios*, especially of the  $^{12}\text{CO}$  and  $^{13}\text{CO}$  isotopomers, which are sensitive to gas densities of a few  $100\text{ cm}^{-3}$ , but also, if available, of high density tracers like HCN, HNC and CN, are powerful diagnostics of the physical properties of the gas they arise from. This requires observations that are still at the limit of what the current generation of mm-telescopes (both single dish and interferometers) can do, since it is essential to observe both higher  $J$  transitions (at least the 2–1 line) and rare isotopomers. The data obtained are then analysed by non-LTE radiative transfer models.

## 2. Sample galaxies

We will now discuss the results of line intensity ratio studies done toward four sample galaxies that show the range of ratios we can expect to encounter. To relate the ratios discussed, a typical value for  $\mathcal{R}_{12/13}(1-0)$  in the Galactic disk is  $\sim 6$  (Polk et al. 1988), (starburst) nuclei typically have  $\mathcal{R}_{12/13}(1-0)$  of 10 – 15 (Aalto et al. 1995), and a few luminous infrared mergers show ‘abnormally high’ ratios of  $> 20$  (Aalto et al. 1991, Casoli, Dupraz, & Combes 1992). The line ratios we have obtained for our sample galaxies are summarized in Table 1.

**UGC 2855 and UGC 2866:** UGC 2855 is a SBc spiral at a distance of  $\sim 20$  Mpc, a weak starburst. UGC 2866, its smaller companion, also has a bar morphology and is a strong starburst with warm dust (IRAS  $60\mu\text{m}/100\mu\text{m}$  ratio

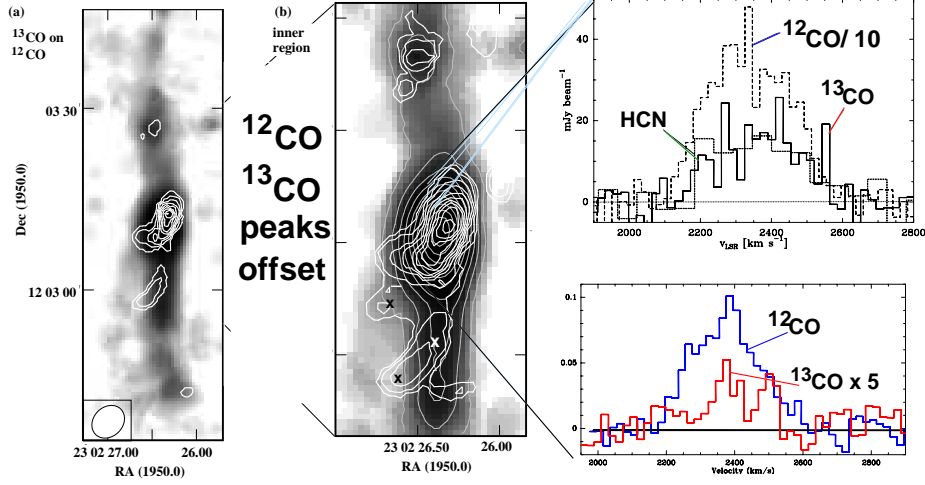


Figure 1. The molecular distribution in the  $^{12}\text{CO}$  and  $^{13}\text{CO}$  (1–0) transitions in the barred starburst galaxy NGC 7479 ( $^{12}\text{CO}$ : greyscale,  $^{13}\text{CO}$ : contours). The right panels (a, b) show the central line profiles; the upper panel displays the (1–0) transitions, measured interferometrically with OVRO, while the lower panel shows the emission in the (2–1) lines, observed at a single dish telescope, the HHT.

$\sim 0.8$ ). We have observed both galaxies with the OVRO interferometer as well as with the OSO and HHT single dish telescopes (Hüttemeister, Aalto, & Wall 1999). UGC 2855, which we believe to be in a ‘pre-starburst’ state without strong bar shocks, still in the process of accumulating gas in the center, is characterized by ‘normal’ values for  $\mathcal{R}_{12/13}(1-0)$  and  $\mathcal{R}_{12/13}(2-1)$  (see Table 1).

In contrast, UGC 2866 has a very high central  $\mathcal{R}_{12/13}(1-0)$  ( $\sim 25$ ), a value so far only encountered in a few starburst mergers. UGC 2866, while a strong starburst, is not a merger, and its FIR luminosity is moderate at  $4.9 \cdot 10^{10} L_{\odot}$ . The value for  $\mathcal{R}_{12/13}(2-1)$  drops into the normal range ( $\sim 10$ ). The high  $^{12}\text{CO}/\text{HCN}(1-0)$  ratio of  $> 38$  (only a limit for the HCN emission could be obtained) is also noteworthy and interesting in a starburst galaxy that should contain a significant amount of dense gas.

**NGC 7479** is a well-studied SBc starburst spiral at  $D = 32 \text{ Mpc}$  (e.g. Hüttemeister et al. 2000, Laine et al. 1999). Globally, i.e. averaged over bar and center,  $\mathcal{R}_{12/13}(1-0)$  is very high, interferometric observations of the central starburst region show significant variations between normal and high ratios, with a ‘high’ average of 23. Within the bar the variation is even more extreme, between extremely high ratios exceeding 40 and disk-like low ratios of  $< 5$ . Again,  $\mathcal{R}_{12/13}(2-1)$  in the starburst center is within the normal range (13) (Fig. 1).

**NGC 4123** is a fairly inconspicuous SBc starburst galaxy with cool dust (IRAS  $60\mu\text{m}/100\mu\text{m}$  ratio  $\sim 0.6$ ). Still, once more we find a high  $\mathcal{R}_{12/13}(1-0)$  value of 26, accompanied by a normal  $\mathcal{R}_{12/13}(2-1)$  of 14 and undetected HCN(1–

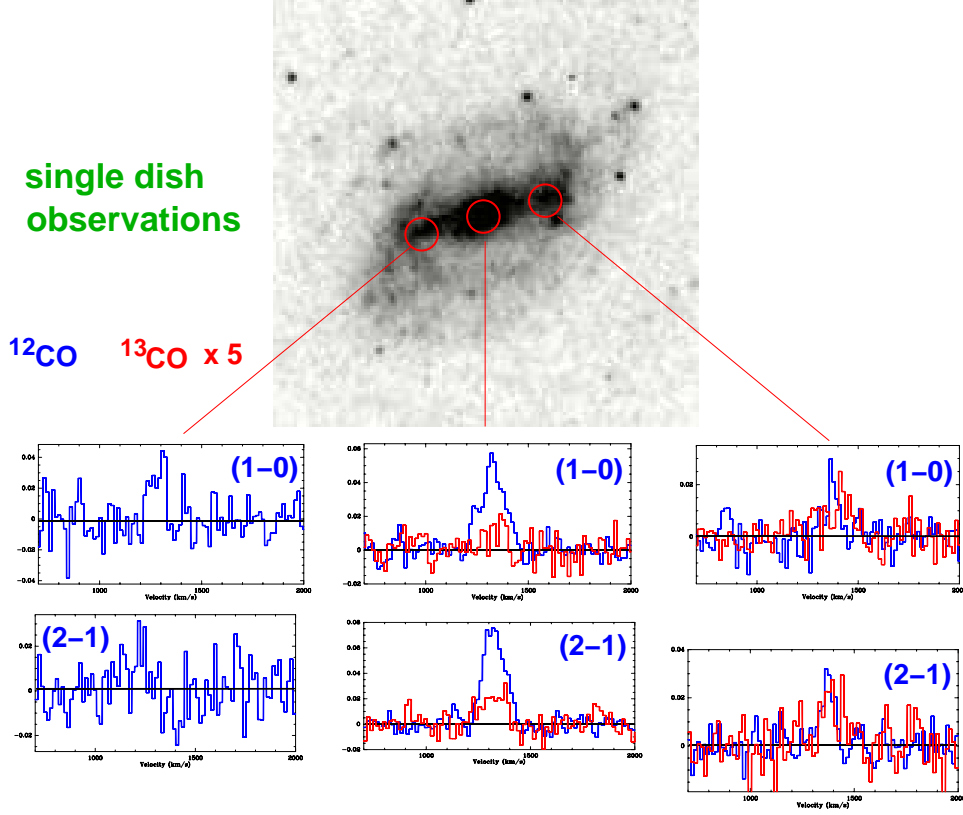


Figure 2.  $^{12}\text{CO}$  and  $^{13}\text{CO}$  (1–0) and (2–1) emission in the barred starburst galaxy NGC 4123 at the indicated positions in the central region and toward the bar ends, observed at SEST. Note the extreme drop in  $\mathcal{R}_{12/13}$  between center and bar end.

0) emission ( $^{12}\text{CO}/\text{HCN}(1-0) > 32$ ) (Fig. 2). The very low (disk-like)  $\mathcal{R}_{12/13}$  of  $\sim 4$  at the bar ends is noteworthy.

### 3. High values for $\mathcal{R}_{12/13}(1-0)$ and scenarios for cloud properties

The observations of the four sample galaxies described above leave us with a somewhat surprising result: There seems to be a class of non-merger barred spiral (starburst) galaxies with moderate IR luminosities that have a high  $\mathcal{R}_{12/13}(1-0)$ , thought to be the exclusive property of a few extreme starburst mergers. While only a minority among the barred spirals as well as the mergers a ‘high-ratio’ galaxies (as will be further discussed in a forthcoming paper examining a larger sample of starburst galaxies, Hüttmeister & Aalto, in prep.), it indicates variations of the dominating component of the molecular ISM within the same morphological group (barred galaxies and mergers). Thus, we can hope that with more detailed modelling we will be able to link these differences in  $\mathcal{R}_{12/13}$  and other line ratios to the evolutionary processes.

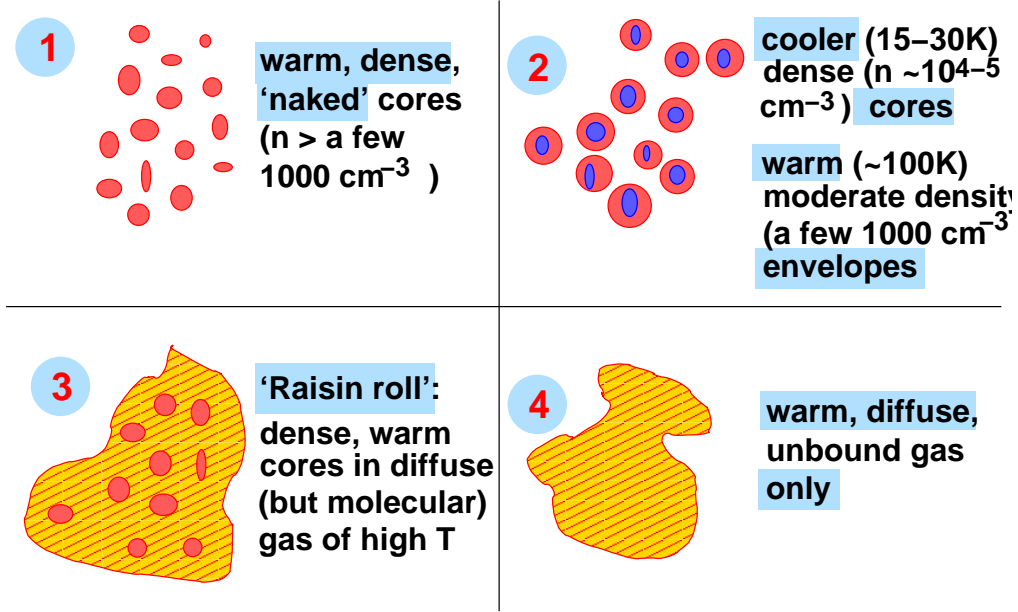


Figure 3. Cartoon of possible scenarios of dominant cloud structure that may be encountered in a (starburst) nucleus, causing different values of  $\mathcal{R}_{12/13}$  as discussed in the text.

Even now, we can examine the standard explanations for high  $\mathcal{R}_{12/13}$  put forward for mergers and see whether they are applicable in a barred starburst environment. Infall of low  $^{13}\text{CO}$ -abundance gas can be excluded for barred starbursts, since typically  $\mathcal{R}_{12/13}$  drops toward the bar ends (see the example of NGC 4123). In situ nucleosynthesis effects in the central starburst also seem unlikely, since high ratios are found as well along the bar. The selective in situ removal of  $^{13}\text{CO}$  (e.g. by selective photodissociation) is possible in principle and may play a role, especially in diffuse gas. However, we typically find that  $\mathcal{R}_{12/13}(2\text{--}1)$  is normal when  $\mathcal{R}_{12/13}(1\text{--}0)$  is high. This may also be the case for most starburst mergers (though the opposite has been claimed by e.g. Taniguchi, Ohya & Sanders 1999) and will be discussed in our forthcoming paper. This behaviour leaves *excitation effects* as the only reasonable explanation.

A simple one-component non-LTE radiative transfer model indicates high temperatures ( $\sim 100 \text{ K}$ ) and moderate densities of a few  $10^3 \text{ cm}^{-3}$  as a possible set of physical properties that cause a combination of high values of  $\mathcal{R}_{12/13}(1\text{--}0)$  and moderate  $\mathcal{R}_{12/13}(2\text{--}1)$ . However, as pointed out in Sect. 1, the molecular ISM in a starburst nucleus certainly consists of multiple components. In Fig. 3, we show a cartoon of different simplified scenarios that may dominate in a starburst nucleus.

Panel 1 depicts the one-component scenario described above. Panel 2 shows a situation that may be realized in many starburst nuclei displaying ‘normal’ values of 10 – 15 in both  $\mathcal{R}_{12/13}(1\text{--}0)$  and  $(2\text{--}1)$ . Clearly, some hot, dense cores are also needed to make a starburst, but it is possible that the dense compo-

ment cools so efficiently that a significant fraction of the material remains at temperatures of 15 – 30 K. In this case, most  $^{12}\text{CO}$  emission arises in the envelopes, while more than half of the  $^{13}\text{CO}$  emission originates in the cores. This scenario is probably realized in NGC 1808 (Aalto et al. 1994). In panel 3, we display a ‘raisin roll’ scenario, with warm cores embedded in a warm, unbound, diffuse intercloud medium. Here, almost all  $^{12}\text{CO}$  emission arises in the diffuse medium, but  $^{13}\text{CO}$  originates almost exclusively in the cores. A medium like this may be encountered in the high pressure environment of extreme starbursts and can give higher  $\mathcal{R}_{12/13}(1-0)$  than (2–1) (Aalto et al. 1995). Finally, the situation described in panel 4, a purely diffuse medium, is unlikely to be realized in starburst nuclei, but may be encountered along a molecular bar. Here, both  $\mathcal{R}_{12/13}(1-0)$  and (2–1) are expected to be high. Clearly, other combinations of the components shown are possible, and in more detailed modelling complementary information, e.g. on high density tracers and possible positional offsets between the distribution of different species have to be taken into account.

#### 4. Conclusions

We have shown that the gas properties of the starburst centers of barred galaxies can be analyzed by means of the line ratios of CO isotopomers. Detailed modelling of the the significant variations encountered can indicate the evolutionary state of the burst. High values of  $\mathcal{R}_{12/13}(1-0)$  found in three sample galaxies are of special interest, since so far these properties were exclusively linked to probably shortlived, extreme burst phases of IR-luminous mergers containing hot dust. We have presented simple scenarios that can explain variations in  $\mathcal{R}_{12/13}$ , all based on changes in molecular excitation.

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